RUNNING IN THE LHC, PART I SUMMARY OF SESSION 7

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INTRODUCTION

During the Chamonix XII workshop in 2003, two sessions were devoted to commissioning the LHC [1,2]. These sessions took a first look linearly in time through the steps of getting the LHC up and running. Once again two sessions have been dedicated to commissioning the machine during the Chamonix XIII workshop. The sessions and presentations this year were designed to be complimentary to last year. Some of the presentations were a direct follow-up of topics raised during the previous workshop.

In session 7 more general beam issues during the commissioning and running in phases of the LHC were treated. Six presentations were made:

- What LHC Operation will look like, R. Bailey
- Increasing radiation levels in the LHC, T. Wijnands
- Operating the LHC at an initially lower energy, R. Schmidt
- Beam-based & reference magnet measurements to compliment the magnet measurement programme, M. Lamont
- Tuneability of the LHC lattice, O. Bruning
- The latest news on electron cloud and vacuum effects, J. M. Jimenez.

WHAT WILL LHC OPERATION LOOK LIKE

Two aspects of the future LHC operation were treated: schedule and performance. Together these two aspects give a picture of what normal operation will be and can also be used to estimate the integrated luminosity per year. As the first year of LHC operation will be rather special, and was in any case treated last year, the presentation here concentrated on the following years and attempted to generate the 'normal' operation scenario after several years of operation.

Schedule

The schedule is designed to give the maximum available time to physics operation. However various other activities are needed to keep the LHC running, these include shutdowns and technical stops for installation, maintenance and repair of accelerator components and services. For the LHC a large fraction of the electronics and control equipment will be installed in underground areas, inaccessible during normal operation. For this reason regular technical stops will be required to check and repair critical components.

In addition, to no-beam periods, machine studies and machine checkout and setup periods will be required during each running period. An initial look through the needs of experiments, equipment groups and services gave the following for a typical year after 2-3 years of operation:

- 11 Week Winter shutdown.
- 3 Weeks cooldown (making 14 weeks total shutdown)
- 2 Weeks machine checkout
- 3 Weeks set-up with beam
- A series of 28-day Physics Cycles consisting of:
    - 21 days of physics
    - 3 days technical stop
    - 3 days machine development
    - 1 day setup with beam

Applying the above formulation leads to an annual running of ~160 days for physics. It should be noted that any major change to the mode of operation – for example passing to ions, or Totem, would require an extended setting up period.

Performance

The first year of LHC operation was treated during Chamonix XII [1]. For year 2 and beyond it is assumed that operation with the 25ns beam will be commissioned and that the intensity will be slowly pushed up. This will require dedicated beam conditioning (scrubbing) periods in the schedule. During the early part of year 2 it is hoped to reach $4\times10^{+10}$ ppb which is approximately the threshold for electron cloud effects. This should yield a peak luminosity of around $2\times10^{+33}$ cm^{-2} s^{-1}.

Taking our knowledge of the luminosity decay, the expected fill duration, the turnaround time and an overall machine efficiency of ~50%, a reduction factor, η, can be defined. Multiplying the peak luminosity by this factor and integrating over the scheduled physics time yields an approximate integrated luminosity for the period. Experience from LEP, together with lifetime calculations for the LHC gives a value of $\eta = 0.24$. For a peak luminosity of $2\times10^{+33}$ $cm^{-2}s^{-1}$ the annual integrated luminosity for 160 days of physics would then be 6 fb^{-1} (40 pb^{-1}/day). With the nominal LHC luminosity of $1\times10^{+34}$ $cm^{-2}s^{-1}$ this will rise to around 36 fb^{-1}/year (200 pb^{-1}/day).

INCREASING RADIATION LEVELS IN THE LHC

During machine operation the loss of energetic primary protons from the beam causes secondary showers. The pions, neutrons and protons produced can have an impact on the equipment, especially electronics, installed in the tunnel. When the beam is switched off there is still a radiation field generated by radioactive nuclei in the accelerator components. This has an impact on the access of equipment for maintenance and repair. These two aspects have somewhat contradictory requirements in terms of additional shielding in the tunnel. The use of additional shielding can protect the delicate electronics as well as other elements of the machine from prompt radiation. However, the shielding itself becomes radioactive with time and also poses an additional overhead for removal before access to the accelerator components can be made. The trade of between these two aspects is particularly important in regions where there are prompt beam losses – including the collimation sections, injection and beam dump regions and around the high luminosity experimental insertions.

For electronics the radiation in the running accelerator has two major effects. One is displacement damage which is a cumulative effects depending on the total dose received. This is not expected to be a problem during the early years of operation. The second effect comes from single event upsets. Here problems with susceptible electronic components may be found even during commissioning. This problem is being tackled by radiation qualification of as many components as possible before installation.

It is clear that the effects of radiation will become progressively more severe as time passes and the beam intensity increases towards the nominal. However, in certain areas, radiation will be an issue almost from day 1. The impact on operations will be to slow interventions in the machine, to allow a cooldown period. In addition, careful preparation and dose analysis for each intervention will be needed to minimize the doses.

RUNNING THE LHC INITIALLY AT A LOWER ENERGY

During Chamonix XII the possibility of running the LHC at a lower energy was already discussed [3]. Here it was noted that the heat load is only marginally reduced at lower energy. It was also noted that the physics potential is reduced at lower energies. The topic has been followed up to complete the picture in two important ways: firstly that there is a bigger margin for particle losses at lower energy and secondly that, although the physics potential is lower, this can be offset by the ability of the machine to produce a larger integrated luminosity.

Figure 1 shows the critical curve for the LHC dipoles. It shows that, by reducing the energy of the machine, additional transient beam losses can be tolerated. During the early period of operation the machine is less well tuned and during critical machine operations – such as the β* squeeze, the possibility of transient losses is rather high. The additional margin would make it less likely that a quench would result, with the associated down-time. However, it should be noted that at lower energy the physical beam size is larger, which might, itself lead to increased losses.

Running at a lower energy of 6, or 6.5 GeV would certainly be of interest if severe problems occur with operation at the nominal energy of 7 TeV. However, it seems more logical to keep this as a 'reserve' and to maintain the idea of initially running at nominal energy.

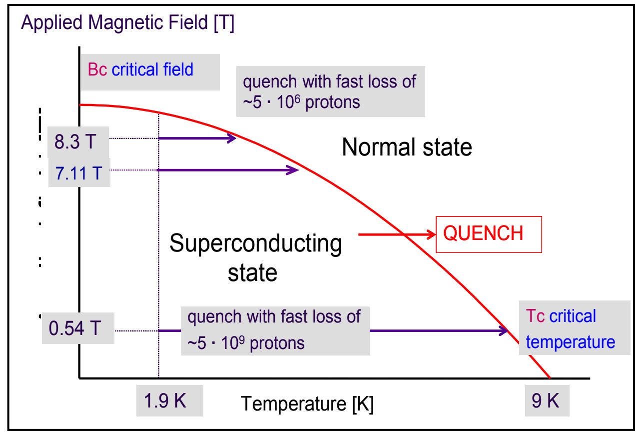

Figure 1: Temperature Margin vs. Field for Dipoles

Magnet Training to >7 TeV

The LHC will in any case one day have to operate at 7 TeV. To be successful with beam, the dipoles must be comfortable running at the nominal field of 8.33 Tesla without beam. During the beam commissioning it will be very important to be able to distinguish between beam related quenches and those relating to the magnets themselves. In order to ensure this it is best to try and make the beam operation at a field where magnet quenches are unlikely.

The present plan assumes that the magnets will require a minimum re-training after installation in the tunnel. This retraining will be done during hardware commissioning to nominal field. However, training the dipoles in the tunnel to a slightly higher field, say 8.6 Tesla, would mean that operation at 8.33 Tesla (7 TeV) should be easier.

BEAM BASED & REFERENCE MAGNET MEASUREMENTS TO COMPLIMENT THE MAGNET MEASUREMENT PROGRAMME

During operation of the LHC the perturbations to the beam coming from field errors in the magnets will have to be very carefully controlled. These errors arise from many sources:

- Static Errors from geometry, collaring, beam screens etc
- Persistent currents
- Eddy currents
- Saturation effects

In addition errors can arise from the absolute knowledge of the transfer function for each magnet and its variation from magnet to magnet for a series.

Many of these effects will be measured during the magnet cold testing programme. However, some of the effects depend critically on the powering history of the magnets and can vary from magnet to magnet. Figure 3 shows the decay and snapback for the b_3 of several dipole magnets. Each one has a slightly different amplitude and time constant. In addition the different offsets are suppressed in figure 3. All these effects must be corrected by a small number of sextupole corrector circuits.

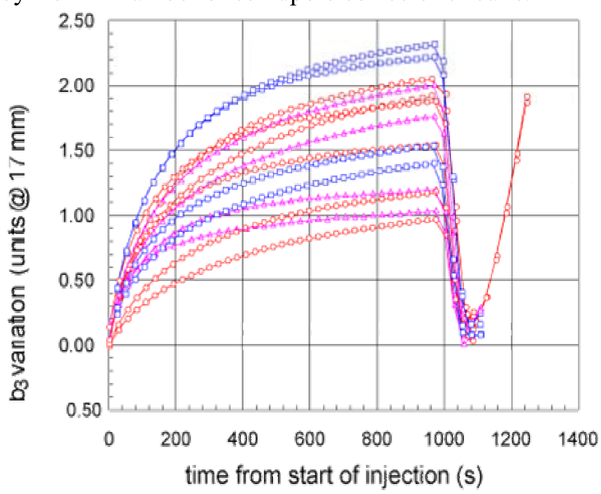

Figure 3: b_3 variation for a series of dipoles during the injection and ramp start

Using the series measurements it is planned to build a model. This will be based on a good empirical knowledge of the processes involved. It must take into account the powering history of the machine and the time evolution of each parameter. After averaging all effects across each octant it will predict b_n at t_o (start of injection plateau) and the time evolution during injection and up the ramp. This model will be refined using feed-forward from beam measurements. In addition it has been proposed that on-line, real-time measurements of the various multipole fields could be made in reference magnets and fed into the correction algorithm.

The question of the need for reference magnets was discussed extensively. Clearly there is a need for a set of magnets, equipped with the relevant measuring devices that can be used to investigate new cycles, or new modes of operation. The ability to run the standard LHC cycle on these magnets is critical. What is less clear is the need to close the loop and use such measurements in real time to control the LHC. A careful analysis of the real needs for machine operation is still needed. In addition, the number powering and choice of reference magnets is still not clear.

TUNEABILITY OF THE LHC LATTICE

The LHC optics needs a certain amount of flexibility to cope with field errors in the magnets and to allow tuning in the machine. There are several sources of errors that appear in the overall machine optics – either as a phase advance error between the two high luminosity experiments, or as an overall tune-split between the two beams. Both are undesirable and must be corrected using the inherent flexibility of the optics and various correction elements. Some of the sources of optics errors are:

- Systematic b_2 in the dipoles (different sign for each aperture).
- Random errors in the dipoles, quadrupoles and in feed down from higher order fields.
- Inner triplet errors
- The design optics in IR7 and IR3 where the phase advance is different for the two beams.

The above effects have been studied in detail. They result in a phase advance difference between IP1 and IP 5 of around $2\pi.0.35$. The net tune split between the two beams may reach around 0.45. These effects must be corrected. In addition small trims to the phase advance between IP1 and IP5 can be used to correct the off-momentum β-beating and non-linear chromatic effects.

The LHC is provided with trim quads. Unfortunately these are not provided at every cell and the phase advance per cell is not exactly 90^o. Complete self cancellation of the optical perturbations is therefore not possible. The use of the trim quads is therefore somewhat restricted by the β-beating they generate.

In addition to the trim quads each insertion region has a certain amount of flexibility. This flexibility is limited on the one hand by the strength of the various quadrupoles and on the other by the aperture of the elements. The flexibility in the IR's has slowly been eroded by various changes to the layouts and the elements. The most recent change – the addition of beam screens in all cold elements has lead to a serious lack of flexibility in these regions.

Before adding beam screens the following tuneability existed in the IRs:

- IR1 & IR 5 ~ ±0.1
- IR 2 & IR 8 ~ ±0.025
- IR 4 ~ ±0.15
- IR 6 ~ ±0.05
- IR 3 & IR 7 ~ 0

The total available tuneability here was 0.45, to be compared with the required 0.35 shown above. With the addition of beam screens the range in each IR has been substantially reduced. In particular IR 4, which was the main region for optics tuning, is now severely limited by the available aperture. The tuning range of IR 4 is reduced by about a factor of 2 with respect to the list above.

The ability to correct the optics is therefore very marginal. In addition, some extra flexibility is always needed. In particular, correction of each optics error at source becomes vital if there is not enough optics flexibility. The ability to disentangle transfer function errors for the many individually powered insertion quadrupoles is not obvious.

In order to minimize the impact of the beam screens a study has been undertaken to rotate the beam screens in locations where substantial gains in the aperture can be gained as a result. Engineering change requests have already been issued for a series of cases.

In addition a study needs to be launched as to the ways and means of increasing the flexibility of the optics in IR4, this being the only location that could conceivably be modified in the future. This log-term study would look at modifications to the layout and include the possibility of adding quadrupoles.

LATEST NEWS ON ELECTRON CLOUD AND VACUUM EFFECTS

The electron cloud effect has been a regular topic at the Chamonix workshops [4,5]. It poses potentially a severe limitation to the performance of the LHC and has thus been studied in detail. The studies take two forms: firstly the development of simulation codes to attempt to model and predict the electron cloud behaviour and secondly an extensive series of measurements in existing accelerators to try to understand the phenomena. The experimental programme is also planned to benchmark the simulations by testing their predictive ability.

The SPS has been used extensively for observations of the electron cloud effect. The availability of the LHC beam, the similar vertical aperture and the fact that the electron cloud is readily generated in the SPS are the main reasons for its use. The electron cloud in a room temperature vacuum system has been studied in detail. More recently experimental installations have be made in the SPS where cold surfaces (<30K) have been tested. The results are both reassuring and worrying.

Figure 4 shows the reduction in electron cloud activity as a function of accumulated beam time for a room temperature system. Figure 5 shows the case of a cold vacuum system. It should be noted that while fig. 4 is drawn on a logarithmic scale, fig. 5 is linear. The initial value of the electron current is similar in the two cases, but the rate at which it goes down is quite different. However, the error bars are rather large and more data is urgently needed to confirm these trends.

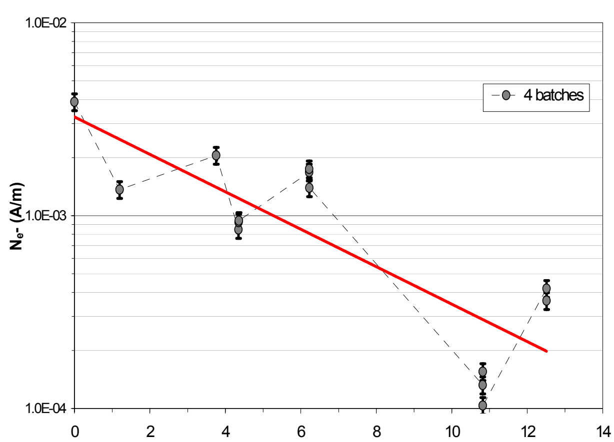

Figure 4: Room Temperature Vacuum Conditioning

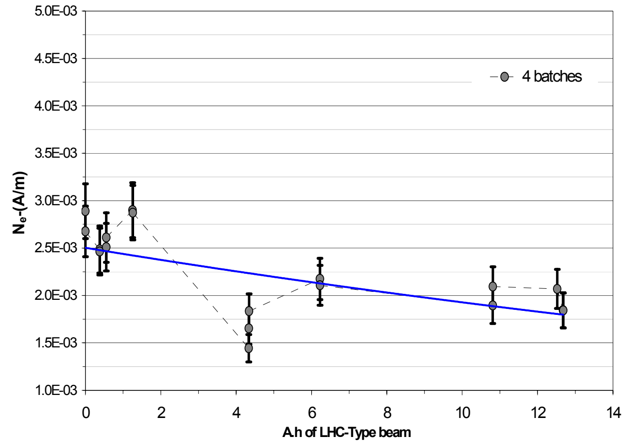

Figure 5: Vacuum Conditioning at 30 K

In the case of the LHC the beam conditioning in the LHC is limited by the available cooling power in the cryogenic system. The beam intensity can therefore only be increased slowly. This is in contrast to the SPS where the intensity is only limited by the vacuum pressure rise. Based on the present knowledge of cold vacuum systems, expected conditioning rates and an upgrade to part of the cryogenic system, the conditioning runs in the LHC will require around 2 weeks at 450 GeV. However many uncertainties still exist.

The SPS will not run in 2005. Since 2004 is the last useful year for such studies in the SPS, a high priority must be placed on confirming the data on vacuum conditioning of cold surfaces. Other related studies on electron cloud effects must also be given a high priority.

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